The inner annular Gap for pulsar radiation: γ-ray and radio emission

G.J. Qiao[1,2], K.J. Lee[2], H.G. Wang[3], R.X. Xu[2] & J.L. Han[1,2]

[1] *National Astronomical Observatories, Chinise Academy of Sciences, Beijing 100012, China*

[2] *Department of Astronomy, Peking University, Beijing 100871, China*

[3] *Center for Astrophysics, Guangzhou University, Guangzhou 510400*

ABSTRACT

The inner annular gap (IAG), a new type of inner gap whose magnetic field lines intersect the null charge surface (NCS), is proposed to explain γ-ray and radio emission from pulsars. The IAG can be an important source for high-energy particles. The particles can radiate between the NCS and the IAG. Some observational characteristics in both γ-ray and radio bands, such as the γ-ray emission beams of Crab-like, Vela-like and Geminga-like, can be reproduced by numerical method. It is predicted that the view angle ζ should be larger than the inclination angle ($\zeta > \alpha$), otherwise the γ-ray radiation will have little possibility to be observed. Whether the inner annular gap (or cap) is sparking (or free flow) depends on the surface binding energy of the pulsar. In stead of neutron star models, the scenario of the IAG is favorable for bare strange star models, because bare strange stars can easily satisfy the requisite condition to form an IAG for both pulsars ($\vec{\Omega} \cdot \vec{B} < 0$) and anti-pulsars ($\vec{\Omega} \cdot \vec{B} > 0$).

Subject headings: pulsars: general — radiation mechanism — strange star

1. Introduction

Both polar cap and outer gap models of γ-ray pulsars have been suggested to explain the high energy emission from pulsars (Ayasli 1981; Harding 1981; Harding et al. 1998; Muslimov & Harding 2003; Zhao et al. 1989; Lu et al. 1990; Lu et al. 1994; Cheng et al. 1976; Ray & Benford 1981; Cheng et al. 1986; Cheng et al. 1996; Hirotani 2000; Romani 1996; Romani 2002). Here, we propose a new scenario of the inner annular gap (hereafter IAG) outside the conventional inner gap. The IAG is defined by magnetic field lines which intersect the null charge surface(NCS) (see Fig.1). As we know, at any point on the NCS the direction of local magnetic field is perpendicular to the rotation axis. So if the radiation region

locates near the NCS (either inside or outside), the pulsar can easily produce a very wide pulse profile (Qiao et al. 2003a). This wide profile will match the observed γ-ray pulse profiles rather well. Some authors (Qiao et al. 2003a; Qiao et al. 2003b; Dyks & Rudak 2003) suggested that if the emission region locates inside the NCS, it would be favorable to understand the γ-ray emission. Here we suggest that the particles flow out from the IAG could be re-accelerated and radiate γ-rays inside the NCS, and the model to account for the γ-ray and radio emission at the same time. In §2 the basic ideas for the IAG are presented. In §3 we show how γ-ray and radio emissions can be produced. Conclusions and brief discussions are given in §4.

2. Details of the inner annular gap (IAG)

Fig. 1 illustrates the magnetosphere of an oblique rotator with a dipolar magnetic field configuration. The magnetic field line 'c' is the *critical field line*, which intersects the NCS at the light cylinder. The radius of the polar cap region defined by the critical field lines in an aligned rotator is $r_{\rm in} = 0.74\Omega^{0.5}R^{1.5}c^{0.5}$ (1). Here R and Ω are the radius and the angular velocity of the star, respectively, and c is the light speed. The cap radius to the foot of the last open field line is $r_{\rm p} = \Omega^{0.5}R^{1.5}c^{0.5}$. There is an annulus between $r_{\rm p}$ and $r_{\rm in}$.

Two kinds of inner vacuum gaps above the polar cap may be formed in some circumstances: the conventional *inner core gap* (ICG) above the central part of the polar cap, and the *inner annular gap* (IAG) above the annular part of the polar cap. If the width of IAG is large enough, the potential drop in the IAG would be high enough so that sparking will be able to take place there. The sparking leads to pair production and generates the secondary pairs, which are accelerated out of the IAG.

For neutron stars, the binding energy of positive particles could be high enough only under some special conditions (Gil & Mitra 2001; Gil et al. 2002) to lead to the formation of an inner vacuum gap. Only one of the inner vacuum gaps can form in the case: an IAG for pulsar ($\vec{\Omega}\cdot\vec{B} < 0$) or an ICG for anti-pulsar ($\vec{\Omega}\cdot\vec{B} > 0$). However the physical condition changes for bare strange stars. The IAG and ICG can form in this case no matter the star is a pulsar or an anti-pulsar since the binding energy is roughly infinite (Xu et al. 1999). The width of IAG is a function of the inclination angle α, as Fig. 2 shows. In the dipolar configuration, the field lines are traced to obtain the shapes of IAG and ICG. When α increases, the width of the annular gap between the magnetic axis and the equator (region A), becomes wider. Higher potential drop can be obtained to produce sparks. While the width of IAG between the rotational and magnetic axes (region B) becomes narrow, and has little chance to form sparks.

Pair cascades can develop in the IAG, and the secondary pairs are produced in an intrinsically non-stationary mode, just as what occur in RS type gap. The secondary pairs are generated as small bundles. In RS gap model these bundles of non-neutral plasma endure no more acceleration out of the gap. Does it still hold true for the IAG scenario? It is probably not, we note that several factors may lead to re-acceleration out of the IAG.

Firstly, due to field line curvature, the net charge density will depart from the local GJ charge density when particles moves along the magnetic field lines, which induces parallel electric fields. This effect is especially strong in the magnetic tube rooted in the IAG, because the GJ charge density varies more sharply than on other open field lines and even the local changes from one sign to the opposite sign when moving across the NCS. Secondly, it was normally suggested that the self-consistent adjustment of the net charge of non-neutral plasma is able to screen the parallel electric fields. However, when charged particles are moving at relativistic velocities and are bunched into bundles, one has to calculate the electric field consulting the Liénard-Wiechert potential rather than the Coulomb potential. It is known that for a relativistic charge particle (with a Lorentz factor γ) the electric field on the moving direction is reduced by a factor of $1/\gamma^2$, then the screen electric field generated by the secondary pairs should be also reduced by a factor of $1/\gamma^2$, which may be neglected to compare with the re-acceleration electric field (Lee 2003).

In this paper we simply assumed that the secondaries are re-accelerated and radiate photons in the region between the NCS and the IAG, then we aim to find whether it is feasible to account for γ-ray and radio properties of pulsar emission. The next section is an endeavor to reproduce the observational properties at γ-ray and radio bands based on the assumption.

3. γ-ray and radio emission from pulsars

Basic picture for γ-ray emission. As it is assumed that γ-ray emission can be produced between NCS and the IAG, also wide pulse profiles can be produced there. To simulate the observations geometry is important. The radiation geometry is shown in Fig. 1 & 3, where ϕ is the azimuthal angle around the magnetic axis, α is its inclination angles, θ is the angle between the magnetic axis and the radiation location r. The angle between the magnetic axis and the NCS, $\theta_{\rm N}$, has the form of

$$\theta_{\rm N}(\phi) = \frac{1}{2}\arccos\left[\frac{\chi\cos\phi\sin\alpha - \cos^2\alpha}{3(\cos^2\alpha + \cos^2\phi\sin^2\alpha)}\right], \tag{1}$$

where $\chi = (8\cos^2\alpha + 9\cos^2\phi\sin^2\alpha)^{0.5}$. The distance from the center of the star to the intersection of last open magnetic field lines and the NCS is denoted by $r_{\rm N}(\phi)$. For a dipole field configuration, $r_{\rm N}(\phi) = R_0(\phi)\sin^2[\theta_{\rm N}(\phi)]$, where $R_0(\phi)$ is the maximum radius of the last open field line. The distance from the star center to the emission point is $r(\phi) = \kappa(\lambda r_{\rm N}(\phi) + (1-\lambda)r_{\rm N}(0))$, where λ and κ are two parameters used to indicate the radiation location. For simplicity, we take λ and κ as 0.8 in our calculations. The physical meaning of $\kappa = 0.8$ is that the radiation positions locate near the NCS and the distance of the radiation location is roughly in proportion to the distance of NCS. $\lambda = 0.8$ means that the distance of radiation location is no exactly in proportion to that of NCS and needs correction, when the NCS locates far form the star.

For the last open field line, the angle between the radiation direction and the magnetic axis, θ_μ, is also a function of the azimuthal angle ϕ, which reads

$$\theta\mu = \arctan\left[\frac{3\sin(2\theta)}{1+3\cos(2\theta)}\right], \tag{2}$$

where $\theta(\phi) = \arcsin[r(\phi)/R_0(\phi)]^{0.5}$. The aberration correction is performed on the θ_μ by numerical procedures. Pulse phase separations can be figured out by direct but lengthy mathematic, which involves the impact angle ξ ($\xi = \zeta - \alpha$). The calculated pulse profiles and parameters are given in the Fig. 4. The width and height of each component in the mean pulse profile are input free parameters. But phase separation are firmly in relation to the parameters α, ξ, λ and κ. The physical considerations for the parameters are as follows.

Physical and geometrical limitation for γ-ray emission regions. The Lorentz factor of the secondary particles out of the inner gap can reach to 10^3 (Zhang et al. 1997). When the secondary moving out from the IAG, they lose their energy through various mechanisms simultaneously, where the inverse Compton scattering plays an important role (Xia et al. 1985; Dyks & Rudak 2000; Zhang & Harding 2000). Magnetic inverse Compton scattering is also an important source of hard gamma-ray photons (Sturner et al. 1995). This means that the hard γ-ray radiation could be produced just out of the gap. However, the position where such γ-rays can escape is limited by the γ-ray attenuation effect in the strong magnetic fields.

A spectral cutoff of γ-ray pulsar above 10 GeV to 100 GeV (Kildea 2003) presents a lower limit of the distance from the emission location from the stellar center. Detailed calculation shows that the 100 GeV photons can only escape from the distance at least above $20R$ for both the Crab (surface magnetic strength B_0 is 3.7×10^{12} Gauss) and the Vela ($B_0 = 3.3 \times 10^{12}$ Gauss) pulsars. We obtain $\kappa > 0.5$ and $\kappa > 0.2$, respectively, for the Crab and Vela pulsars in the model.

The calculation indicates that the parameters of both λ and κ will affect the phase

separation between two peaks of the γ-ray light curve. For parameters of Crab and Vela (see Fig. 4), we find $\kappa \in [0.8, 0.99]$ and $\lambda \in [0.65, 0.85]$ for Crab, and $\kappa \in [0.65, 0.83]$ and $\lambda \in [0.77, 0.99]$ for Vela, respectively, for 10% change of phase separation of two peaks. The values of κ and λ indicate that the main radiation region is confined near the NCS.

Radio emission. The ICS model (Qiao & Lin 1998; Xu et al. 2000; Qiao et al. 2001; Qiao et al. 2002) is involved in our IAG model to account for the radio emission. The secondary pairs streaming out from the polar cap cascade with typical energy $\gamma = (1 - \beta^2)^{-0.5} \sim 10^3$ will scatter the low frequency waves produced in sparking, and the up-scattered frequency reads $\nu \simeq 2\gamma^2\nu_0(1 - \beta\cos\theta_{\rm i})$ (for $B \ll B_{\rm q} = 4.414 \times 10^{13}$ Gauss), where $\theta_{\rm i}$ is the incident angle (the angle between the moving direction of the particle and the incoming photon).

The differences between the observed radio and γ-ray pulse profiles are very significant. Fig. 4 shows the calculated Crab-like, Vela-like and Geminga-like light curve for both radio and γ-ray band under reasonable parameters. The observed pulse profiles in gamma-ray and radio bands are reproduced for seven pulsars: the Crab, PSR B1509-58, the Vela, PSR B1706-44, PSR B1951+32, the Geminga (no observed radio emission) and PSR B1055-52 (Qiao et al. 2003a; Qiao et al. 2003b).

4. Conclusions and discussions

We emphasize here that the IAG and the NCS play an important role in pulsar γ-ray radiation. At least the IAG can be a source of high energy particles for pulsars emission. If the radiation region locates near the NCS, many radio and γ-ray observational facts can be easily understood. The large phase separation of components of γ-ray light curves and the relative compact radio phase separation reveal that the γ-ray radiation region should locate near the NCS. The geometry calculation partly supports this radiation location.

It is indicated from the calculation above that the condition of γ-ray pulsars which we observed is that the view angle ζ should be large than the inclination angle, i.e. $\beta > 0$. This is because that the part of IAG between the magnetic axis and the equator is wider so that it gain higher potential drop, when the inclination angle becomes larger.

The luminosity of γ-ray pulsars in the IAG model depends on the maximum potential drop across the gap, $\Delta V = 0.5\Omega B r_{\rm p}^2 c^{-1}$. For a given Lorentz factor we find that the γ-ray luminosity are proportional to $\dot{P}^{0.5}P^{-1.5}$, which is in agreement with observations.

Our IAG scenario is intrinsically different from the free-flowing type of polar cap model

(Muslimov & Harding 2003). How does the IAG interact with the outer gap? Are pulsars bare strange stars or special kind of neutron stars (Gil et al. 2002)? Does the radiation come from the re-accelerated non-stationary pair flow or free flow? All these questions need to be investigated further more. The details of the IAG model, such as the re-acceleration and radiation processes, γ-ray luminosity, spectral behaviors, emission beam properties and so on, will be discussed in separated papers.

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REFERENCES

Ayasli, S. 1981, ApJ, 249, 698

Cheng, A., Ruderman, M. & Sutherland, P. 1976, ApJ, 203,209

Cheng, K.S., Ruderman, M. A. & Zhang, L. 2000, ApJ, 537, 964

Cheng, K. S. , Ho, C. & Ruderman, M. A. 1986, ApJ, 300, 500

Dyks, J., & Rudak, B. 2000, A&A, 360, 263

Dyks, J., & Rudak, B. 2003, ApJ, 598, 1201

Gil, J. A., Mitra, D. 2001, ApJ, 550, 383

Gil, J. & Melikidze, G. I. 2002, ApJ, 577, 909

Harding, A. K. & Muslimov, A. G. 1998, ApJ, 508, 328

Harding, A. K. 1981, ApJ, 245, 267

Hirotani, K. 2000, PASJ, 52, 645

Kildea, J. 2003, astr-ph/0305580

Lee, K. J., Thesis for Bachelor degree, Pking Unoversity

Lu, T. & Shi, T. 1990, A&A, 231, L7

Lu, T., Wei, D. M., & Song, L. M. 1994, A&A, 290, 815

Muslimov, A. G. & Harding, A. K. 2003, ApJ, 588, 430

Qiao, G. J. & Lin, W. P. 1998, A&A, 333, 172 (ICS I)

Qiao, G. J., Liu, J. F., Zhang, B. & Han, J. L. 2001 A&A, 377, 964 (ICS II)

Qiao, G. J., Lee, K. J., Wang, H. G. & Xu, R. X. 2003, in: High Energy Processes, Phenomena in Astrophysics, Proceedings of IAU Symposium No. 214, eds. X. D.Li, Z. R. Wang & V. Trimble, p.167

Qiao,G. J., Lee, K. J., Wang, H. G. & Xu, R. X. 2003, ASP Conference Series, edited by Bailes, M, Nice, D. J. & Thorsett, S. E., 302, 183

Qiao, G. J., Wang, X. D., Wang, H. G. & Xu, R. X. 2002, ChJA&A, 2, 361

Ray, A. & Benford, G. 1981, Phys. Rev. D, 23, 2142

Romani, R. W. 1996, ApJ, 470, 469

Romani, R. W. 2002, astro-ph/0211064

Ruderman, A. M. & Sutherland,P.G. 1975, ApJ, 196, 51 (RS75)

Sturner, S. J., Dermer, C. D., & Michel, F. C. 1995, ApJ, 455, 736

Xia, X. Y., Qiao, G. J., Wu, X. J., & Hou, Y. Q. 1985, A&A152,93

Xu, R. X., Qiao, G. J. & Zhang,B., 1999, ApJ, 522,L109

Xu R. X., Liu J. F., Han J. L., & Qiao G. J. 2000, ApJ, 535, 354 (ICS III)

Xu, R. X.,Zhang, B., & Qiao, G. J. 2001, Astroparticle Physics, 15, 101

Zhang, B. & Harding, A. K. 2000, ApJ,532,115

Zhang, B., Qiao, G. J.,& Han, J. L. 1997, ApJ,491,891

Zhao, Y. H., Lu, T., Huang, K. L., Lu, J. L. & Peng, Q. H. 1989, A&A, 223, 147

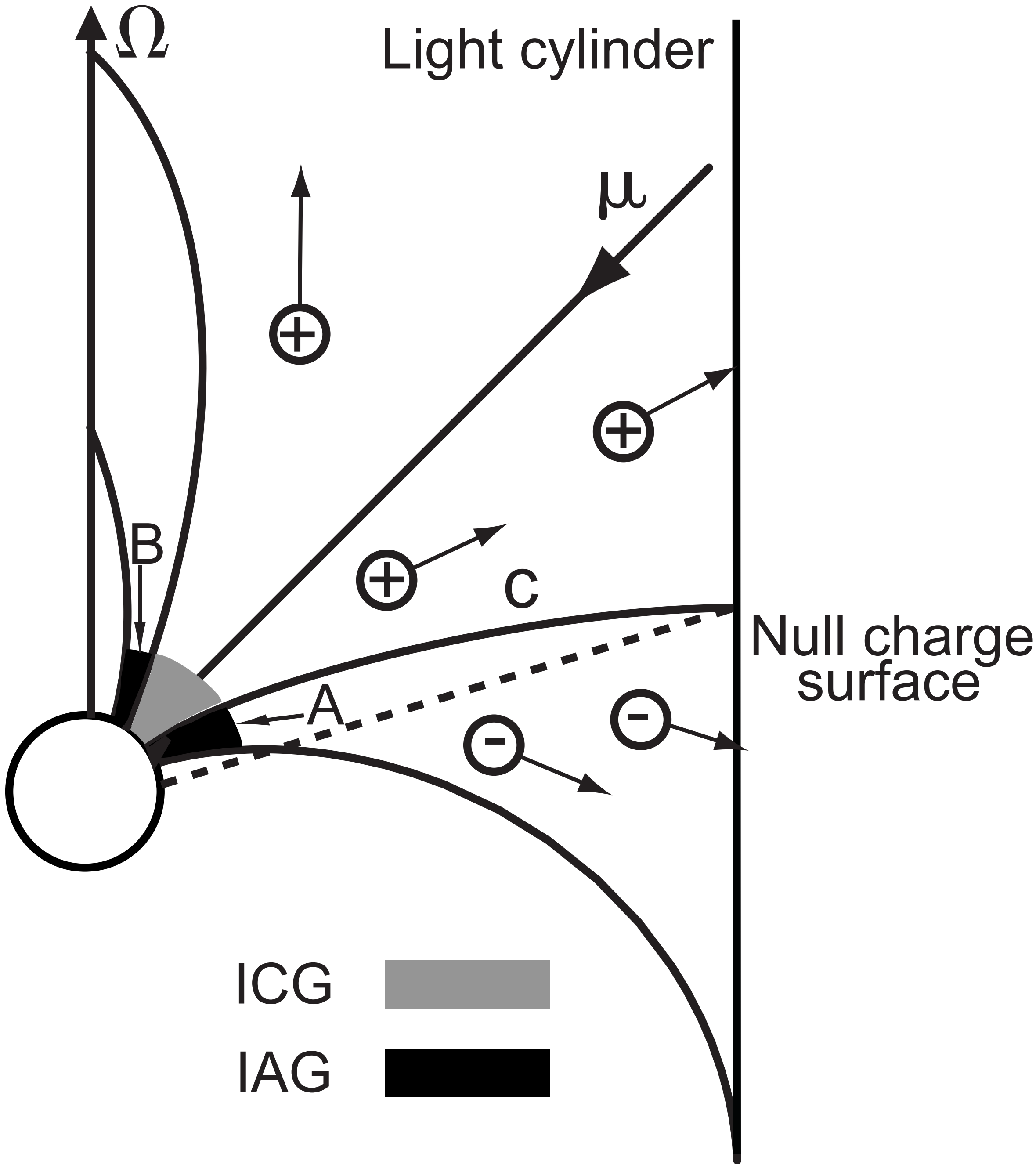

Fig. 1.— The inner annular gap (IAG), the inner core gap (ICG) and the null charge surface (NCS) of an oblique rotator. If the center star is a strange star, both IAG and ICG can form. For neutron stars, at most only one inner gap can be formed. Region 'A' and 'B' correspond to the region 'A' and 'B' on Fig. 2.

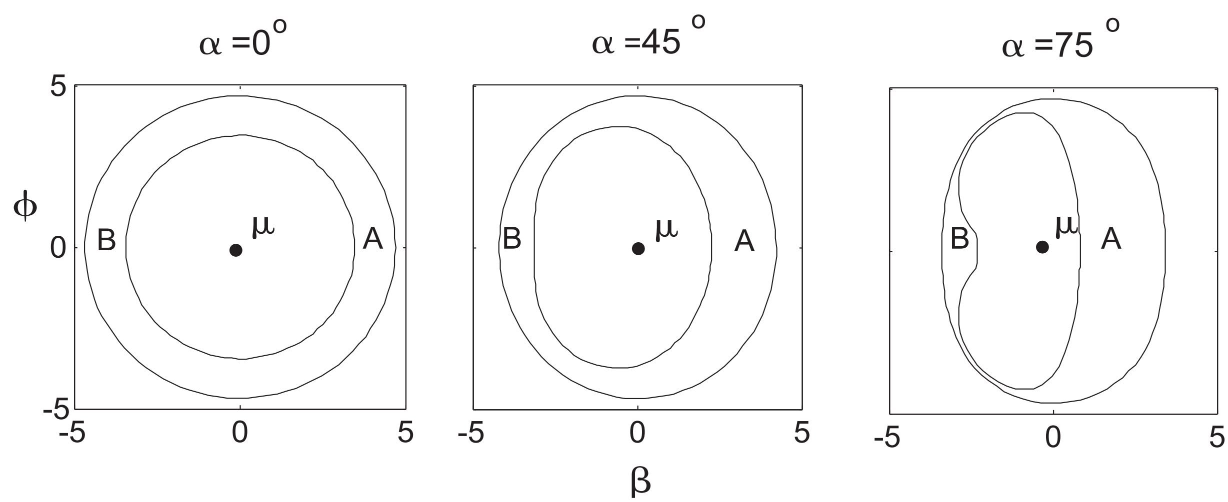

Fig. 2.— The shape of the inner annular gap(IAG) and the inner core gap(ICG) for different inclination angle α. A dipole configuration is used in the calculations. We take radius of light cylinder $R_{\rm cl} = 1500$km and the radius of pulsar $R = 10$km.

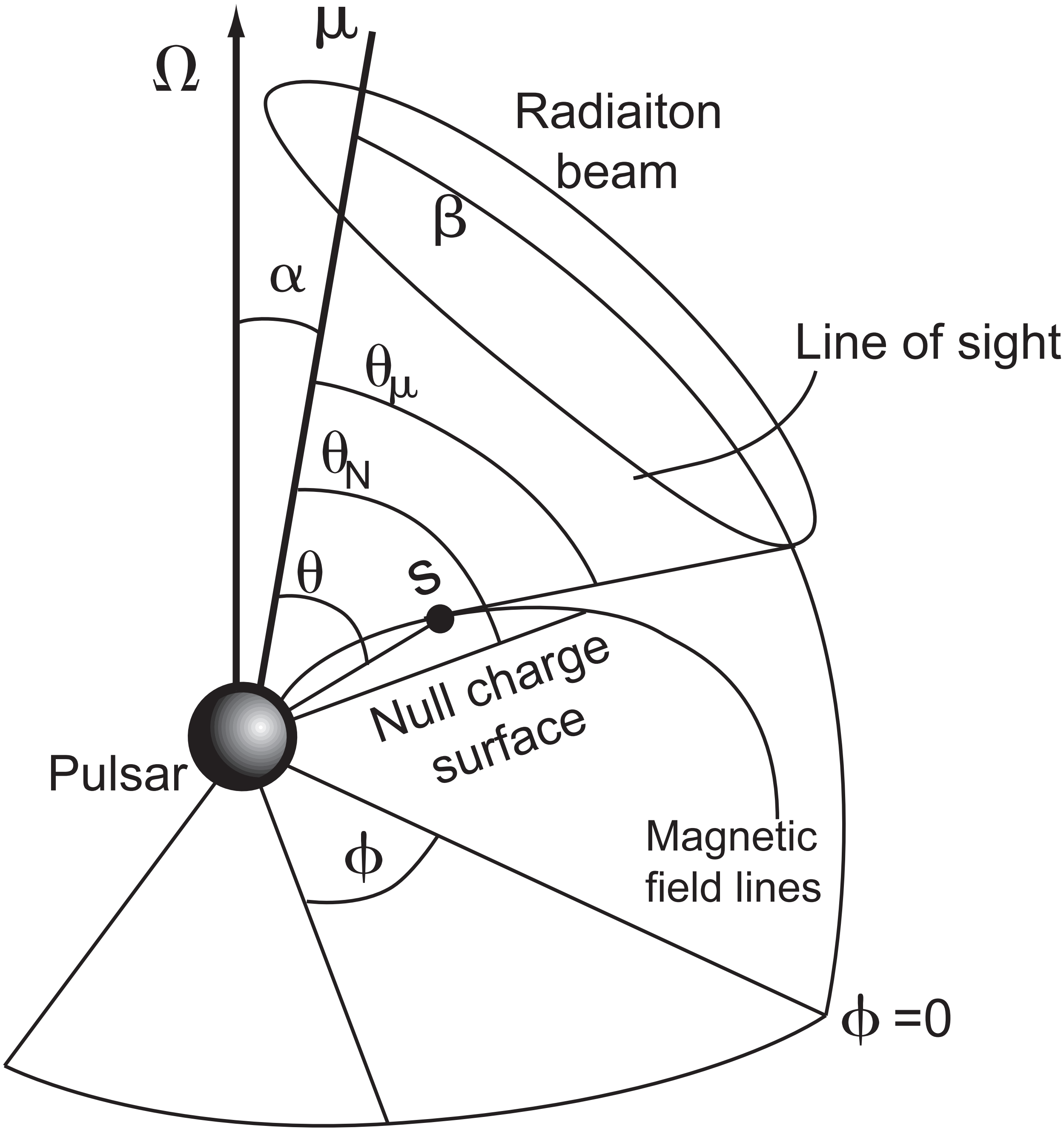

Fig. 3.— The radiation geometry of a pulsar. ϕ, ζ and α are the azimuthal angle respect to magnetic axis, the viewing angle and the inclination angle, respectively. θ, θ_μ and $\theta_{\rm N}$ denote the angle between the magnetic axis and the radiation source S, the radiation direction and the null charge surface respectively. Owing to the aberration effect and the asymmetry of the NCS respect of magnetic axis, the radiation beam is asymmetric.

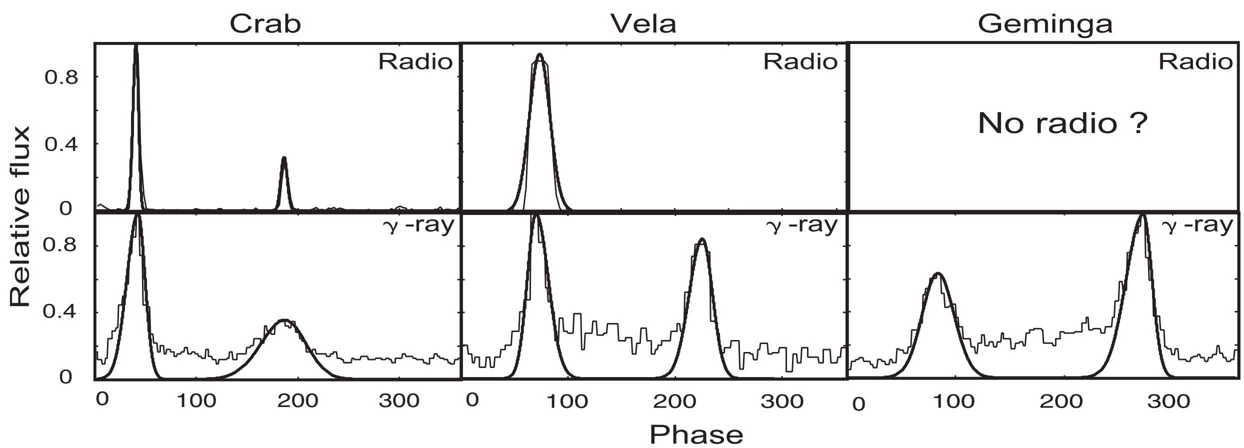

Fig. 4.— The theoretical and observed Crab-like, Vela-like and Geminga-like light curve at both radio and γ-ray bands. The γ-ray and radio data are derived from Thompson 2003 and the European Pulsar Network Data Archive respectively. The parameters listed in the figure are just for reference. If phase separation is determined with 10% error, we found that $\alpha \in [36, 49], \zeta \in [39, 57], \kappa \in [0.8, 0.99], \lambda \in [0.65, 0.85]$ for Crab and $\alpha \in [33, 44], \zeta \in [51, 61], \kappa \in [0.65, 0.83], \lambda \in [0.77, 0.99]$ for Vela. We do not give parameters for Geminga light curve, the parameters can not get only from γ-ray light curve.